

# **Energy-food nexus in the marine environment: a macroeconomic analysis on offshore wind energy and seafood production in Scotland**

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## **Abstract**

The rapid development of offshore wind farms (OWFs) has stimulated debate about its overall socioeconomic impacts. Expanding the scale of OWFs increases the availability and affordability of electricity but could displace existing fishing activities and reduce food supply. To evaluate these impacts from a macroeconomic perspective, a computable general equilibrium (CGE) model is developed, using Scotland as a case study. A particular focus is placed on the disaggregated electricity and seafood sectors, their interconnectedness from an energy-food nexus perspective, and the distributional effects across household groups. This paper explores, from macroeconomic perspective, the trade-offs in the energy-food nexus between expanding OWFs and the seafood sectors, together with the impacts on food and energy security. The results suggest that, through economic linkages, increasing the number of OWFs would have a negative, but limited, effect on seafood production sectors. However, the falling cost of electricity from OWFs would have a positive impact on the economy overall and benefit lower income households, contributing to a reduction in fuel poverty. The model results raise the awareness of nexus linkages between OWFs and seafood production and are applicable to policies involving the development of other offshore renewables.

**Keywords** Energy-food nexus; Offshore wind energy; Computable general equilibrium model; Fuel poverty.

## 1. Introduction

The UK Government plans to reach net-zero greenhouse gas (GHG) emissions by 2050 under the Paris Agreement (HM Government, 2019). To eliminate carbon emissions, the energy mix is moving towards electrification, with the increased electricity supply generated from renewable technologies providing low-carbon, sustainable energy (National Grid, 2019). Not only is offshore wind one of the fastest growing renewable energy technologies, but the UK has the largest installed capacity, which stood at 7,905 MW in 2018 (The Crown Estate, 2019). To encourage electricity generation from renewable sources, the UK government introduced Renewable Obligations (RO) (BEIS, 2012) and later established the Contracts for Difference (CfD) scheme which financially supported the rapid development of offshore wind farms (OWFs) (BEIS, 2015a). CfDs incentivise the development of OWFs by guaranteeing a (typically subsidised) stable sale price for renewable energy electricity generation amidst volatile wholesale electricity prices (BEIS, 2018). With the support from CfDs, the capacity of OWFs has increased by over 400% while costs have fallen by more than 60% after three auction rounds (AR). As shown in Table 1, the successful OWF projects won support in the most recent AR3 at a strike price of around £41/MWh. This is lower than the wholesale electricity price and thus would count as subsidy-free renewables. This record-low price is likely to encourage further official support and faster development of OWFs. Already the UK Government has signed an offshore sector deal under which OWF capacity is expected to increase to 30 GW by 2030 (HM Government, 2019).

CfD Allocation round (AR)	Year	Total UK capacity (MW)	Scotland capacity (MW)	Average strike price (per MWh in 2012 prices)	Average wholesale electricity price in 2012 (per MWh)
AR1	2014	1162	448	£117	
AR2	2017	3196	950	£64	£48.2
AR3	2019	5466	466	£41	

**Table 1** Three Rounds of Contracts for Difference Allocation of Offshore Wind Energy in UK

(Source: BEIS, 2019, 2017, 2015b; Ofgem, 2019.)

However, the rapid development of OWFs raises concerns over possible tensions between OWFs and the fisheries sector, with a potentially reduced seafood supply from the marine environment. Such conflicts, and associated trade-offs, are appropriately framed in the context of the Food-Energy-Water (FEW) nexus, which is an integrated approach capturing interconnections, dependencies and linkages among energy, food and water resources within the environmental, economic and societal scales (FAO, 2014; Hoff, 2011; Salmoral and Yan, 2018). When considering the OWFs and seafood sectors, however, the interaction is restricted to energy-food, since no fresh water is involved. As the marine environment is increasingly vulnerable to economic, social and environmental shifts (Austen et al., 2018), the energy-food nexus between OWFs and seafood production is increasingly becoming the subject of research.

There are indirect macroeconomic linkages between OWFs and seafood production from the energy-food nexus perspective. On the production side, expanding OWFs could shift resources away from the seafood sectors, for example through fishermen adapting their skills to meet employment in the OWFs sector rather than in fishing. This could indirectly affect food supply through increasing the cost of production, thereby also impacting on household seafood affordability. On the consumption side, both energy and food are essential commodities in household budgets; energy makes up 8.1% of all UK household spending with electricity representing half of the household energy budget (Advani et al., 2013). Food consumed at home comprises 18.3% of budgets, with fish accounting for 5% of total food spending (ONS, 2019). Through the consumption linkage, potential changes in the price of electricity generated by OWFs will affect the purchasing power for food. In particular, reducing the cost of OWFs may have important effects on household electricity consumption and particularly on fuel poverty in lower-income households.

Fishing activities can also be directly affected by OWFs because fishermen are either forbidden to operate within the OWFs or are reluctant to fish within these areas due to concerns about navigational safety and inadequate space between turbines for the safe deployment of their gear (Alexander et al., 2013; Mackinson et al., 2006). Fishermen might switch their fishing grounds away from OWF development areas, resulting in them fishing in unfamiliar areas. This is likely to lead to lower catches,

catches of alternative species with different price profiles or higher increased operating costs for fishing vessels (Alexander et al., 2013; Gray et al., 2016; Hooper et al., 2015; Mackinson et al., 2006). Conflicts such as these would result in lower fishing productivity and thus reduced market availability of fish, which would further impact the overall economy through the macroeconomic linkages. However, whilst a number of studies have taken the nexus approach between offshore wind energy and seafood from environmental (e.g. Bailey et al., 2014; Bergström et al., 2014; Hooper et al., 2017) or societal perspectives (e.g. Hattam et al., 2017; Papathanasopoulou et al., 2015), very little quantitative research has been undertaken on potential macroeconomic interactions. Therefore we lack a holistic economic analysis of conflicts and trade-offs between OWFs and seafood sectors, and an evaluation of the distributional effects across different socioeconomic groups.

A Computable General Equilibrium (CGE) model is a comprehensive macroeconomic assessment tool consisting of a mathematical representation of a market economy based on theoretical general equilibrium principles. Such models are often used to quantifying the economy-wide impacts of renewable energy development, including aggregate macro-economic impacts (e.g., Boeters and Koornneef, 2011; Böhringer and Löschel, 2006) and overall welfare changes (e.g., Böhringer et al., 2013). Furthermore, a CGE model is suitable for nexus analysis since it can evaluate impacts that operate through the price mechanism, revealing the interlinkages between economic agents relevant for nexus elements (Kretschmer and Peterson, 2010). In other words, the CGE model allows assessment not only of sectoral impacts on nexus elements induced by changes in one nexus element through the interconnections in the model but also the overall impacts on the economy as a whole. Reviews of CGE models used to assess the nexus approach are given in Dai et al. (2018), Endo et al. (2020), McCarl et al. (2017), Zhang et al. (2019). Specific work focussing on the energy-food nexus regarding biofuels and agriculture include Arndt et al. (2012), Nkolo et al. (2018), Ringler et al. (2016), Timilsina et al. (2012, 2011). A CGE model is therefore a suitable tool to quantify the nexus linkage associated with expansion OWFs and seafood through the production and consumption processes as those identified above.

However, the existing CGE literature focuses only on single components of, rather than the interconnections between, nexus elements. The CGE model has been applied to assess the wider macroeconomic impacts of marine renewables (e.g. Allan et al., 2014; Cohen and Caron, 2018; Dalton et al., 2016; Graziano et al., 2017; Lecca et al., 2017), but no particular attention has been paid to sectoral impacts on seafood productions. Meanwhile, the CGE model has also been applied to analyse the impacts of regional fishery policies on seafood production (e.g. Finnoff and Tschirhart, 2008; Floros and Failler, 2004; Pan et al., 2007; Seung and Waters, 2010) and distribution effects across households (e.g. Hoagland et al., 2015; Jin et al., 2012). No CGE model has so far been applied in an energy-food nexus framework to evaluate the impacts of an exogenous shock on both OWF and seafood sectors and the distributional effects on household expenditures.

To fill this gap, we develop a CGE model to comprehensively assess the economic impacts of the development of OWFs and the interactions with the seafood productions through the incorporation of macroeconomic linkages from the energy-food nexus perspective. Specifically, this analysis focuses on how the expansion of OWFs would change seafood and electricity availability and affordability, and therefore consequently have distributional effects across household groups, using Scotland as the case study area.

## **2. Method**

### **2.1 Study Area**

The marine environment plays an important social and economic role in Scotland. Scotland's offshore waters are approximately six times the area of its landmass and provide productive and diverse resources (Scottish Government, 2015). Globally, fish accounts for 17% of animal protein and the demand for fish is increasing at 2.9% per annum (FAO, 2018). Scotland provides various kinds of seafood from both sea fishing and aquaculture, and these also act as key inputs to the fish processing sector. In 2017, almost two thirds of total UK fish landings came from Scotland with vessels based in Scotland landing 453 thousand tonnes of sea fish and shellfish with a value of £316 million gross value added (GVA) (MMO, 2018; Scottish Government, 2018a). Meanwhile, aquaculture production is growing to meet the increasing demand for seafood, which generated £436 million GVA in 2017 (Scottish Government,

2018a). The increasing fishing and aquaculture production results in fish processing being an additional important seafood sector, contributing £392 million GVA to Scottish economy in 2017 (Scottish Government, 2018a). Seafood production is also culturally and politically important in Scotland and is expected to remain commercially significant with the constantly increasing domestic and export demand for seafood (Scottish Government, 2015).

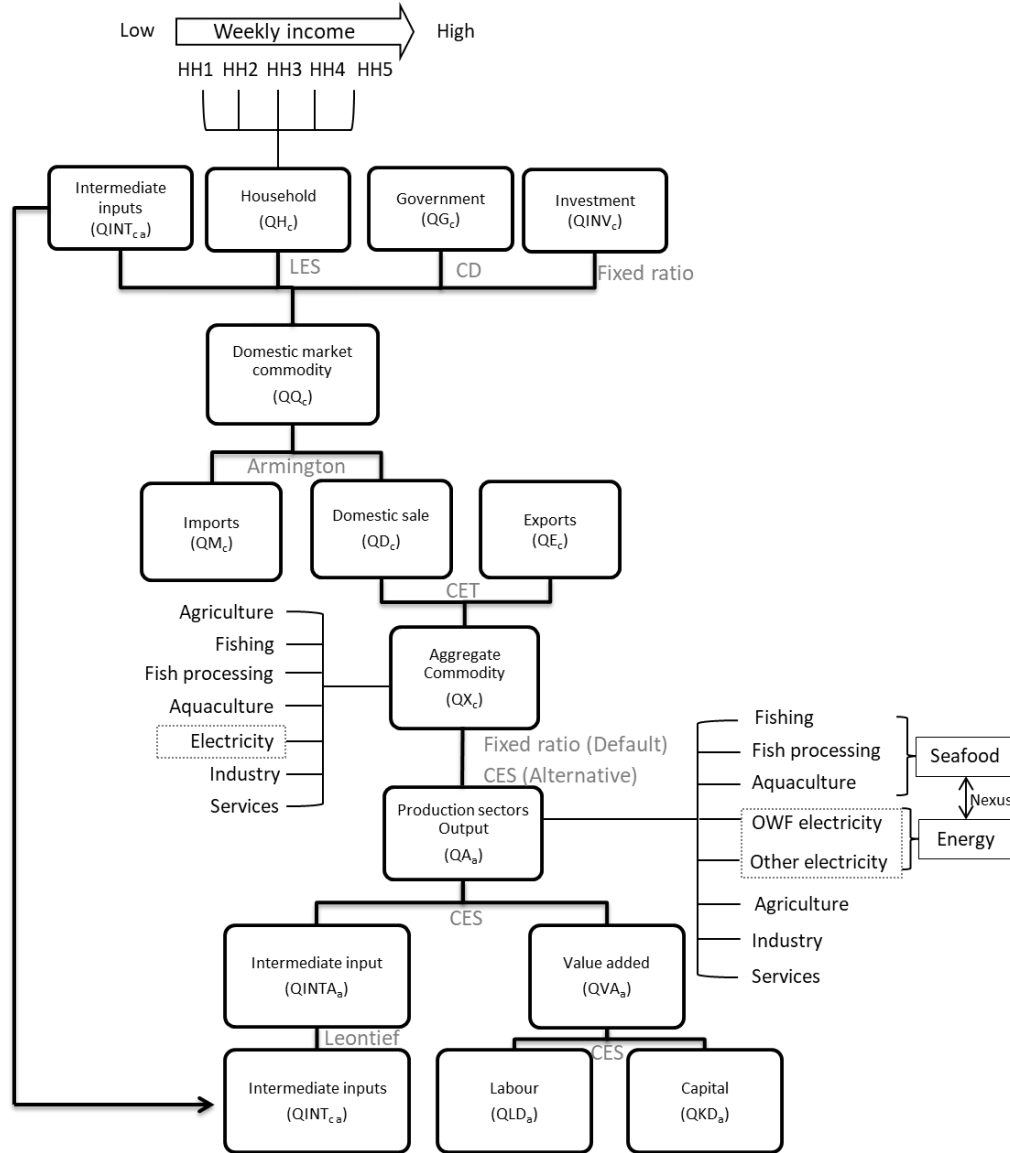
Scotland has abundant offshore wind resources and therefore offers huge potential for offshore wind energy (Scottish Government, 2018b). With access to such a resource, the Scottish Government has set an ambitious target to generate 100% of Scotland's gross electricity consumption using renewable technologies, including offshore wind, by 2020 (Scottish Government, 2018b). In 2018, Scotland had reached 55% of electricity generated from renewable sources with 217 MW of operational offshore wind and had approval granted for a further 4.2 GW (Scottish Government, 2018b).

## **2.2 CGE Model Data and Structure**

A CGE model is an appropriate tool for nexus analysis as it tracks the availability of nexus elements through the allocation of factors of production and changes in production outputs. It can also evaluate the affordability of nexus commodities by measuring the changes in prices and thus impact on household consumption behaviour and welfare distribution.

The CGE model used in this study is the Scottish Economy Marine Model (SEMM) and is based on the International Food Policy Research Institute (IFPRI) Standard CGE model framework (Löfgren et al., 2002). This framework has been modified in two major ways. First we incorporate both OWFs and seafood production as independent sectors within the model economy. Second, households have been explicitly disaggregated into five income groups to allow the assessment of distributional effects. Figure 1 shows the model structure and contains information on all key assumptions made for each economic agent. The model is a single-country static CGE model for Scotland and is solved using the General Algebraic Modelling System (GAMS). Model calibration is based on the latest 30 sector Social Accounting Matrix (SAM) for Scotland for 2013 (Katris et al., 2019). This is augmented with data from two additional sources. The first is the energy-disaggregated 2010 UK Input-Output table to disaggregate the Scottish electricity sector (Allan et al., 2019). The second is the 98 sector 2013 Scottish

IO table which has production information on the disaggregate the seafood sectors (Scottish Government, 2020). Details of the construction of the 8-sector SAM are given in Appendix A and the SAM itself is shown as Table A1.



**Figure 1** Nested structure of the CGE model

In the model, the decisions made by economic agents are the outcome of the optimisation of objectives, subject to a number of constraints, within a coherent economy-wide framework. Producers maximise their profits subject to technology constraints, where production is represented as a nested structure that allows flexibility at different levels. Essentially, the output in each sector is determined by constant elasticity of substitution (CES) production functions that permit substitution between inputs based on

relative price changes. In each sector, the intermediate input is a Leontief composite. This means that commodities that make up this composite are combined in fixed proportions.

As shown in Figure 1, the model distinguishes eight production sectors resulting in seven commodities, with three seafood and two electricity production sectors. The seafood sectors are ‘fishing’, ‘fish processing’ and ‘aquaculture’, whilst for electricity generation ‘OWF electricity’ and ‘other electricity’ are identified separately. The disaggregation of seafood and electricity sectors are further explained in the Appendix A and the sector decomposition is shown in Table A2. These two electricity sectors are further combined, with fixed coefficients as the default option, into a single composite electricity commodity sold in the market. However, as part of the sensitivity analysis, simulations are run in which the production of the composite electricity commodity is generated via a CES function whose components are the outputs from the ‘OWF electricity’ and ‘other electricity’ sectors. For all other commodities, there is a one-to-one association between the production sector and the corresponding commodity.

The SAM is calibrated on 2013 data. At that time Scotland had only 190 MW of installed OWF capacity, contributing less than 1% of total electricity generation (Scottish Government, 2019). To facilitate modelling the impact of OWFs, an estimate of the size of this growing sector is required (Phimister and Roberts, 2017). The sector is expected to make up around 10% of the total UK electricity generation by 2020 (HM Government, 2019).<sup>1</sup> In the initial calibration of the model, we therefore retain the figure for total electricity generation but adjust the share produced by the OWF sector to 10%. This assumption provides a useful reference point to identify the present economy-wide impacts of developing OWFs (Arndt et al., 2012).

The remaining three sectors are agriculture, industry and services. These are highly aggregated but represent the reactions of the rest of the economy to changes in those production sectors that are of particular interest, that is the two electricity and three seafood sectors. Aggregation helps to simplify

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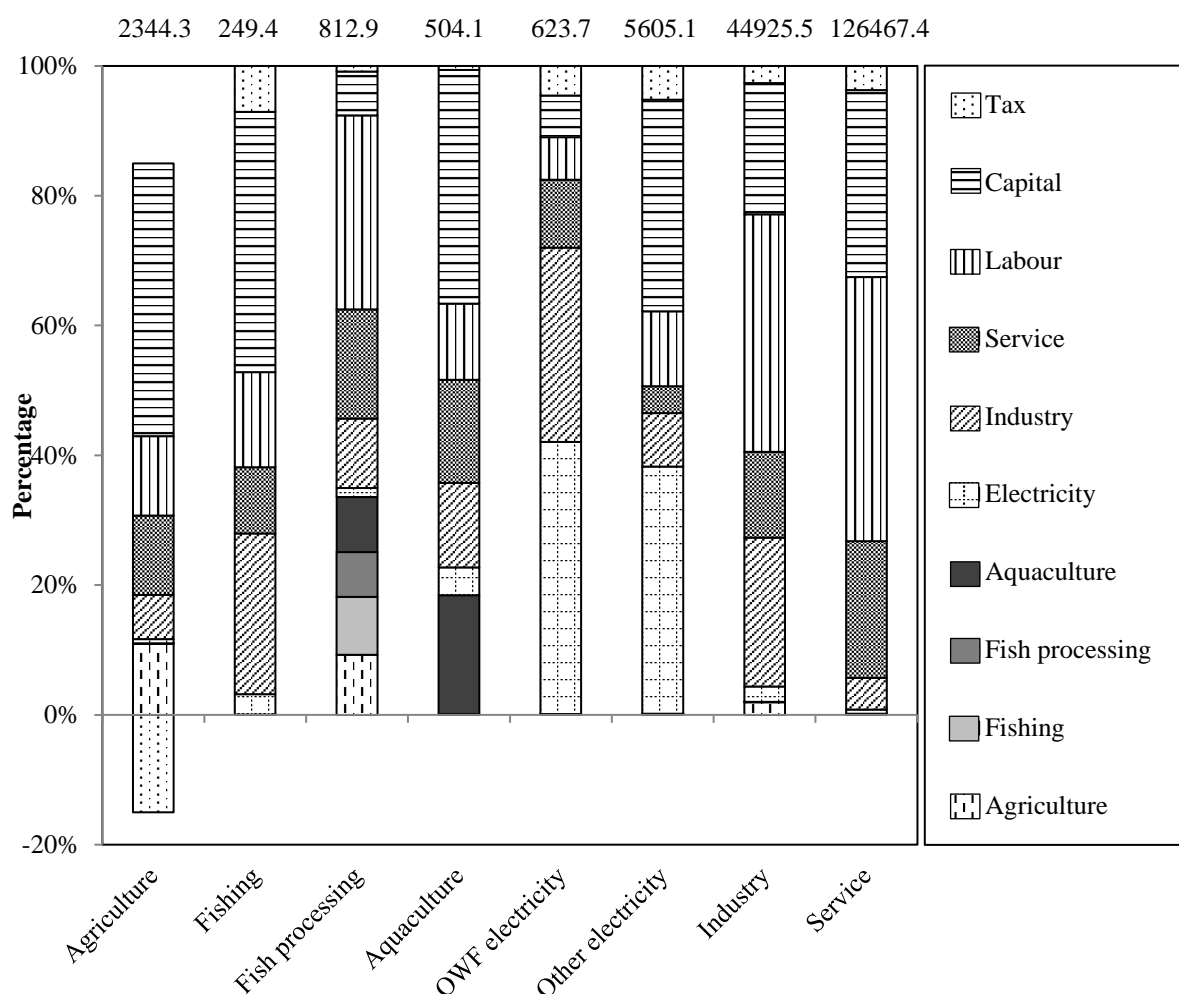
<sup>1</sup> OWFs accounted for 8% of the total electricity generation for the UK as a whole in 2018 and almost 7% for Scotland in 2019 (Scottish Government, 2019; The Crown Estate, 2019).

the model construction but it can lead to bias in the level and distribution of the estimated impacts across such aggregated sectors (Lenzen, 2011; Miller and Blair, 1985; Su et al., 2010).

To test if the aggregation leads to significant bias on seafood and electricity sectors, we calculated the Type 1 IO multipliers for the 8×8 Leontief inverse matrix embedded in the SAM and these values are shown in Table A3 in Appendix A. For the seafood sectors, these multiplier values are compared to the corresponding figures from the fully disaggregated 2013 Scottish IO table. For the electricity sectors the comparison is with the OWF sector in the electricity-disaggregated 2010 UK IO table and the aggregated electricity sector in the 2013 Scottish table.

The multiplier values give an indication of the strength of the local linkages captured in the data. The results show that there are no marked or systematic variations in the multipliers for the seafood and electricity sectors between the aggregated and disaggregated multipliers. This suggests that aggregating the remaining sectors does not result in huge bias on results of how the impacts of expanding OWFs distributed among two electricity and three seafood production.

The base-year sectoral production input intensities are shown in Figure 2. These reflect the information given in the 2013 Scottish SAM and describe each sector's production structure. They are important in determining the way that a sector's competitiveness is affected by variations in input prices, particularly for capital and labour. Small sectors will tend to have production structures that differ from the average by a greater extent than do large sectors. This means that their competitiveness will tend to respond more strongly to the changes in input prices that are generated by exogenous shocks. Like the electricity sectors, fishing and aquaculture are relatively capital intensive, while fish processing is relatively labour intensive. Intermediate input demand linkages also create a channel through which a shock in one sector is transmitted to other sectors. Among the three seafood sectors, fishing and aquaculture are important intermediate inputs for the fish processing sector while aquaculture needs relatively more electricity as a production input. Both electricity sectors require a large amount of electricity as an intermediate input.



**Figure 2** Production input intensity of production activity sectors with total output above (in £million).  
(Data source: Allan et al., 2019; Katris et al., 2019)

As this is an open economy model, substitution possibilities are allowed between production for domestic and non-domestic markets. The model employs the small-country assumption that the country is a price-taker in the single external market, which comprises both the rest of the UK and the rest of the world. Export decisions are modelled based on the assumption that producers maximise profit given domestic and export prices. This occurs under the assumption of imperfect transformation between domestic sales and exports, which is represented by a constant elasticity of transformation (CET) function. Furthermore, commodities in the domestic market are supplied by a combination of domestic production and imports, where imports are determined by the Armington assumption which allows

imperfect competition. All the production elasticities are listed in the Appendix A Table A4 and consumption elasticities can be found in Table A5.

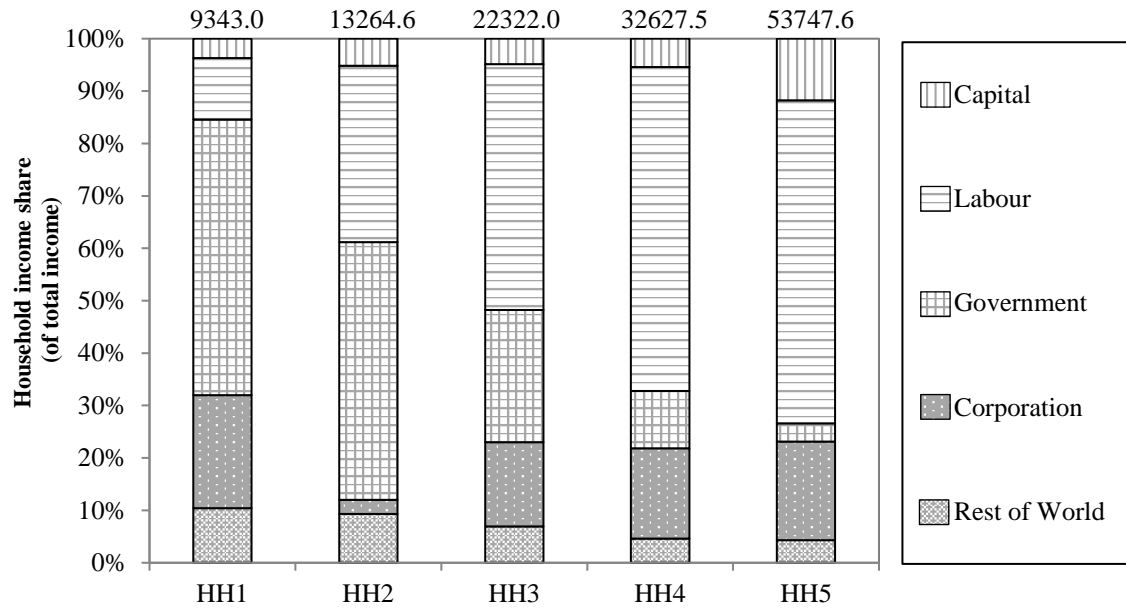
The model distinguishes household income quintiles, with weekly income increasing from HH1 to HH5. As shown in Figure 3, lower income household groups (HH1 and HH2) receive a greater share of their income from government transfers, in the form of welfare and state pensions, while household groups with higher income (HH3, HH4 and HH5) are relatively more dependent on wage and capital income. Household income from wage and capital rental payments is endogenous and driven by production activities whereas transfers from government are treated here as constant, indexed to the consumer price index (CPI).

To determine aggregate household expenditure, savings, payments of taxes and transfer payments to other institutions and the rest of the world are subtracted from household income. The commodity composition of household consumption is determined using a linear expenditure system (LES), which distinguishes commodities as necessary and luxury goods. Food (i.e. agriculture, fishing, fish processing) and energy (i.e. electricity) are typically considered as necessary goods which have low income elasticity. Industry, services and aquaculture are treated as luxury goods for lower income households but as necessities for higher income households.<sup>2</sup>

Government revenues consist of all taxes and transfer payments from other institutions and the rest of world. Total government expenditures comprise consumption on commodities determined by a Cobb-Douglas utility function, transfers to other institutions (e.g. social welfare to households), and savings. All household, government and foreign savings are summed and equal total investment to form the equilibrium condition. Welfare is measured using the Hicksian equivalent variation (EV) method. This measures the income needed to make households as well off in the new equilibrium evaluated at benchmark prices.

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<sup>2</sup> Aquaculture is considered as a luxury good because aquaculture fish is more expensive than capture fish (OECD, 2018).



**Figure 3** The share of different income sources for household quintiles with income increasing from HH1 to HH5 with mean annual income shown at the top of each column (in £million). (Data source: Katris et al., 2019)

Simulation results are sensitive to the model closure rules. For the present model, these are shown in Table 2. They were chosen to reflect the relative size and openness of the Scottish economy. The fixed supplies of capital and labour are assumed to be fully employed, with factors mobile between sectors and equilibrium achieved through economy-wide flexible wages and capital rentals. Finally, the gross domestic product (GDP) deflator is chosen as the model's numeraire so that price changes in simulation results are reported relative to this numeraire.

Model closure	Assumption	Justification
Government	Fixed tax rate	To focus on impacts on households, government is simplified.
Current account	Fixed foreign savings	To avoid the misleading welfare effects that appears when foreign savings change.
Saving-investment	Fixed investment	Flexible household saving rate. Correspondence with fixed capital supply.
Factor market	Fixed factor supply	Factors have enough time to adjust to be fully mobile between activities.

**Table 2** Summary of model closure assumptions (Source: Löfgren et al., 2002)

It is important to note that SEMM is a simulation, not a forecasting, model. Its stripped down character, and in particular its static nature and fixed aggregate factor supplies, are designed to focus on the key aspects of the nexus interactions that are our concerns. These are the impacts on the distribution of resources across sectors and incomes across households.

### 2.3 Scenario Simulations

The nexus implications of the expansion of OWFs are explored through a set of scenarios. In Scenarios 1 and 2 the exogenous shock generates an expansion in the OWF sector but in both simulations this has no direct effect on the efficiency of fishing sector. However, the model captures the economy-wide competition for capital and labour and the demand interactions implicit in each sector's supply chain through the identification of macroeconomic linkages. Scenario 3 takes as the exogenous shock a direct reduction in the efficiency of the fishing sector. This is assumed to be due to the interference of OWFs with fishing activities acting as a direct impact of the expansion of OWFs. Table 3 summarizes the three scenarios considered in this study.

Model scenario	Impact assumptions	Shocks in model
Scenario 1	Second round of CfDs auction (AR2)	30% higher cost of and 35% subsidy on the OWF sector
Scenario 2	Third round of CfDs auction (AR3)	15% lower cost of the OWF sector
Scenario 3	Increasing fishing effort due to OWFs	10% decrease in productivity of the fishing sector

**Table 3** Simulated OWFs production scenarios for Scotland in the CGE model (Source: BEIS, 2019, 2017, 2015b; Scottish Government, 2018c)

The first two scenarios highlight and compare the expansion of OWFs under two contrasting situations. Scenario 1 introduces an exogenous 30% reduction in efficiency of production in the OWF sector, which points to the situation reflected in the second round of CfD auctions (AR2) where the average strike price, £64/MWh, was 30% higher than the average wholesale price of electricity of £48.2/MWh. The CfD scheme would subsidise the renewable energy, which has a higher cost, to ensure that electricity generation is moving towards low-carbon. In order to achieve the expansion in output a 35% subsidy is simultaneously imposed to cover the high cost of OWFs. This subsidy is introduced as a negative *ad-valorem* tax to the OWF sector. Scenario 1 therefore represents a subsidised expansion in OWFs where the sector is facing higher costs with increased scale. This scenario reflects the path to decarbonisation if the renewable technologically is inherently increasingly costly and resource intensive.

In Scenario 2, the increased price competitiveness takes the form of a 15% improvement in OWF efficiency. This reflects the situation in the third round, AR3, of the auction of CfDs where the record-low average strike price of £41/MWh compared to the average wholesale electricity price of £48.2/MWh. Scenario 2 therefore shows the impact of an expansion in electricity generation powered by increasingly efficient renewables and reflects a more optimistic vision for moving towards zero carbon.

The initial share of OWFs in the electricity generation is 10% and the default setting for the model assumes a fixed ratio between OWFs and other electricity in the domestic production of electricity to

ensure the competitiveness of higher production cost OWFs, as required by the government's target for renewables. An alternative CES function is available for combining the OWF and other electricity sectors. With the CES function and an increase in OWF price competitiveness, expanding OWF production will not only increase the output of electricity as a whole, but also the share in electricity from OWFs. In this case, the elasticity between OWF and other electricity represents the sensitivity of the trade-off that the national grid is prepared to make across different generation types. For that reason we test how sensitive the results in Scenario 1 and 2 are to variation in this elasticity value.

The aggregate effect of the direct impact on fishing activity from expanding OWFs is explored in Scenario 3. In this case fishing efficiency is assumed to fall due to a reduction in fishing opportunities (e.g. Alexander et al., 2013; Gray et al., 2016). In Scenario 3 this is simulated through the introduction of an exogenous 10% decrease in the productivity of all inputs in the fishing sector (Scottish Government, 2018c).

### **3. Results**

#### **3.1 Sectoral impacts on production activities and commodity sales**

In Table 4 we report the percentage changes in the level and price of the eight sectoral production outputs (QA, PA) and the level and price of the seven domestic market commodities (QQ, PQ) for all three scenarios. Results for other important variables (i.e., value-added, QVA; intermediate input used, QINTA; imports, QM; exports, QE; and their prices) are shown as percentage changes in the Appendix B, Tables B1 and B2.

First, note that in each simulation reported in Table 4, the proportionate changes in the domestic output for 'OWF electricity' and 'other electricity' sectors are exactly the same. This is because, as discussed in Section 2.3, the two electricity sectors are assumed to have a fixed share in the electricity generation mix. Although the percentage increases in the domestic OWF electricity outputs are similar in both Scenario 1 (+5.34%) and Scenario 2 (+5.81%), the output price changes are quite different (-5.16% and -13.83% respectively). In Scenario 1 the positive impact of the subsidy outweighs the negative impact

from the higher cost of OWFs in Scenario 1, so the reduction in output price is much less than in Scenario 2.

However, the increase in electricity commodity sales is greater in Scenario 1. The explanation reflects the relatively large amount of electricity that is used in the production of electricity. In Scenario 1, OWF production is expanding together with a reduction in the efficiency with which it is produced: this implies that the electricity input per unit of output of OWF increases. However, in Scenario 2 the input of electricity per unit of OWF falls. This difference in the demand for electricity as an intermediate input accounts for the counterintuitive electricity sales results.

Where electricity production expands, other elements of the economy, apart from the industry sector, are typically negatively impacted. The expansion of OWFs requires the net transfer of labour and capital from other sectors. This includes the seafood sectors. As argued earlier, being smaller sectors they are likely to have more idiosyncratic cost structures. This implies that these sectors are more likely to deviate from the average reaction to exogenous shocks and are more sensitive to movements in the prices of production inputs. Among three seafood sectors, the fishing and aquaculture sectors are most strongly affected. This is primarily because - similarly to the electricity sectors - they are relatively capital-intensive, as shown in Figure 2. The fish processing sector suffers some knock-on effects from reductions in the capture and aquaculture fish supplies. The sales of seafood tend to change less than their outputs because more expensive seafood results in reduced demand, both in domestic and export markets. Also as a result of inter-sectoral movement in capital and labour, production in aggregated agriculture and services sectors falls, whilst the output of the industry sector increases slightly, being an important input for electricity production. The sectoral domestic production directly impacts the corresponding commodity sales and prices.

In Scenario 3, the reduced productivity in the fishing sector has negative impacts, particularly on the seafood sectors. The output of the fishing sector falls by over 13% with a 0.58% increase in price. Outputs in fish processing, aquaculture and agriculture also decrease due to a reduction in fish to be used as a production input. The non-food sectors experience minor output increases, benefited from labour and capital released from the small seafood sectors. The decline in domestic production of

seafood also negatively impacts seafood export and seafood demand so that the import and commodity sales both decrease.

Variable	Scenario 1	Scenario 2	Scenario 3
<b>Domestic production activities (Supply)</b>		<i>Production sector Output (QA)</i>	
Agriculture	-0.36	-0.71	-0.02
Fishing	-2.75	-3.36	-13.49
Fish processing	-1.41	-1.86	-4.24
Aquaculture	-5.49	-5.11	-1.49
Other electricity	5.34	5.81	0.06
OWF electricity	5.34	5.81	0.06
Industry	0.33	-0.11	0.07
Services	-0.25	-0.06	0.02
		<i>Price of Domestic Output (PA)</i>	
Agriculture	0.12	0.15	-0.02
Fishing	0.07	0.05	0.58
Fish processing	0.03	0.03	0.17
Aquaculture	0.11	0.07	-0.03
Other electricity	-0.22	-0.75	-0.02
OWF electricity	-5.16	-13.83	-0.01
Industry	-0.01	-0.01	0.00
Services	0.02	0.05	0.00
<b>Domestic sale commodities (Demand)</b>		<i>Domestic market commodity sales (QQ)</i>	
Agriculture	0.02	-0.16	-0.11
Fishing	-1.31	-1.68	-3.87
Fish processing	-0.35	-0.24	-0.63
Aquaculture	-3.35	-3.23	-2.33
Electricity	3.98	1.83	0.01
Industry	0.33	0.01	-0.01
Service	-0.21	0.05	0.00
		<i>Price of domestic market commodity (PQ)</i>	
Agriculture	0.12	0.15	-0.01
Fishing	0.22	0.24	1.67
Fish processing	0.08	0.10	0.32
Aquaculture	0.30	0.24	-0.11
Electricity	-0.72	-2.10	-0.01
Industry	-0.01	-0.01	-0.01
Service	0.03	0.06	0.00

**Table 4** Percentage changes (%) in production activity and commodity sales for different sectors

### 3.2 Changes in household income and welfare distribution

Table 5 shows the differences in the distributional impacts across household groups. In all scenarios the impact on incomes is small across all households. In Scenarios 1 and 2, as OWFs expand, other sectors are forced to release both capital and labour. Because the electricity sectors are relatively capital intensive, the economy-wide capital rental rate rises and the wage falls. Household incomes depend more heavily on wage payments so all households show slightly reduced incomes. The increasingly inefficient OWFs expansion, as outlined in Scenario 1, results in slightly larger negative changes in household incomes. Moreover, the incomes of lower-income households vary less than those of higher-income households, whose incomes rely more heavily on wages and capital rental (Figure 3). The change is similar in Scenario 3 but the variations in wage and capital rentals are so small that there are only minor impacts on household incomes.

The household welfare is valued by EV in income. This shows that under Scenario 1 welfare falls for all household quintiles with no consistent trend over household income. In Scenario 2 all households experience a welfare improvement with lower income households consistently benefitting the most. Decreased fishing productivity in Scenario 3 again has only slight impacts on households, as fishing is a small sector in the economy.

Variable	Scenario 1	Scenario 2	Scenario 3
<i>Household income</i>			
Labour wage	-0.13	-0.11	0.02
Capital rent	0.26	0.32	-0.03
HH1	-0.01	0.00	0.00
HH2	-0.03	-0.02	0.01
HH3	-0.05	-0.04	0.01
HH4	-0.07	-0.05	0.01
HH5	-0.05	-0.03	0.01
<i>Household welfare (equivalent variation in household income)</i>			
HH1	-0.20	0.16	0.00
HH2	-0.20	0.12	0.00
HH3	-0.21	0.10	0.00
HH4	-0.21	0.07	0.00
HH5	-0.17	0.07	0.00

**Table 5** Percentage change (%) in household income, commodity consumption and welfare

### 3.3 Macroeconomic impacts

The macroeconomic results show that the expansion in OWF output accompanied by a reduction in OWF efficiency, as in Scenario 1, has an overall negative impact on GDP (-0.21%). In contrast, the increased efficiency of electricity from OWFs in Scenario 2 produces a small increase in GDP of 0.08%. In Scenario 3, decreasing productivity in the fishing sector has a negligible impact on the economy at a macro scale.

For all three simulations, the proportionate changes in real absorption are reported in the second row of Table 6. Real absorption is defined as the sum of private consumption, government spending (results shown in Appendix B Table B3) and gross investment (assumed to be fixed in the model). GDP equals real absorption plus the trade balance (total exports – total imports). The proportionate change in GDP is the weighted sum of the proportionate changes in real absorption and the trade balance. In first two scenarios, the proportionate change in the real absorption dominates in determining the change in GDP. In Scenario 1, the proportionate change in GDP is heavily influenced by the negative change in real absorption arising from decreased household consumption. In contrast, in Scenario 2 GDP increases as cheaper electricity causes the real absorption to increase significantly to cover the trade deficit. There is no significant change in Scenario 3. The total exports decrease slightly reflecting the falling domestic production of seafood whereas the total imports also fall slightly due to decreasing demand. The decline in total exports and total imports balance the trade deficit, together with no significant change in real absorption, resulting in no change in GDP.

Variable	Scenario 1	Scenario 2	Scenario 3
Gross domestic product (GDP)	-0.21	0.08	0.00
Real absorption	-0.25	0.10	-0.01
Total exports	0.10	0.03	-0.04
Total imports	0.15	0.05	-0.05

**Table 6** Percentage changes (%) in macroeconomic variables in different scenarios simulated

## 4. Discussion

### 4.1 Model results: implications for energy security and the macro-economy

Concerns over electricity price volatility have previously been raised in part because of fear that renewable technology policies aimed at reducing carbon emissions might result in fuel poverty, given that electricity is a necessity to all households (Advani et al., 2013; Teller-Elsberg et al., 2016). The results from Scenario 1 show that increasingly inefficient OWF production can be stimulated by a CfD scheme that incorporates subsidised price reductions. However, the energy security to households is not increased because energy affordability falls as a result of lower incomes. The increased electricity production in this case mainly goes to government consumption (Table B3) and exports (Table B2). Only when the reduced price of OWF output is driven by increased efficiency, as in Scenario 2, do households experience increased energy affordability and a corresponding rise in household consumption. Based on differential patterns of consumption, electricity price changes have differential impacts on the welfare of different household groups.

An analysis of household energy use in the UK revealed that energy makes up 16% of lower-income household spending but for just 3% of higher-income household spending (Advani et al., 2013). Variation in the electricity price therefore makes the welfare of the lowest income group (HH1) the most sensitive to the modelled energy shocks discussed in this paper. The record-low price of OWFs (simulated in Scenario 2) in AR3 implies significant reduction in fuel poverty through much cheaper electricity. This especially helps lower-income households as against the varying electricity prices driven by fossil fuel price volatility (Fuss and Szolgayová, 2010).

It is often argued that growth in renewable energy generation brings economic benefits through increased investment and employment (Phimister and Roberts, 2017). However the model assumes fixed capital and labour supply and thus results in Scenario 1 that although the subsidy under the CfD scheme stimulates the development of OWFs when the cost is higher than generation using fossil fuels, it has a negative impact on GDP. These results suggest that the development of OWFs would only have conventional economic benefits when the cost is brought down so that production becomes subsidy-free, as in Scenario 2.<sup>3</sup> Furthermore, the macroeconomic benefits are strongly related to the local supply

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<sup>3</sup> It is important to note that the conventional GDP calculation does not take into account any environmental improvements that would accompany Scenarios 1 and 2.

chain; higher local content could generate greater GDP growth (Graziano et al., 2017) and employment (Gilmartin and Allan, 2015). Based on Scenario 1 results, the current local content for OWF supply chain is not enough to bring economic benefits though output in the industry sector has increased in response to higher demand from the expansion in OWFs. In addition, the SEMM has a highly aggregated industry sector. As indicated by the multiplier (Table A3), the aggregated multiplier would misrepresent industries in its subcategory, which would lead to underestimate the impacts from local supply chain. With subsidy-free production and the anticipated increase in local supply content, the enhanced economic benefit is likely to further encourage the development of OWFs, in accordance with the net-zero emission target of the Scottish Governments.

#### **4.2 Model results: implications for food security**

Optimism over subsidy-free OWFs is countered by uncertainty over possible trade-offs between OWFs and seafood production, and further detrimental effects that changing seafood supplies may have on food security. Expanding production of OWFs under both the higher and lower cost cases (Scenarios 1 and 2 respectively) is expected to have negative impacts on seafood production because production factors (labour and capital) are bid away by expanding OWFs. The major direct and negative impact on seafood production is through the displacement of fishing effort caused by OWFs and this is the focus of Scenario 3. Such a reduction in fishing productivity and the accompanying decreases in production in seafood sectors would normally be ignored in a macroeconomic analysis of OWFs. Our results show that the negative impacts of a fall in fishing productivity are significant for the fishing sector, but would be largely confined to the three seafood sectors. Declining fish supplies from the fishing sector further negatively impacts the fish processing and aquaculture sectors through the macroeconomic linkages because fish is clearly an important intermediate input. Similar concerns have also been observed for the agriculture and biofuel nexus where biofuel production raises agricultural prices through competition for limited resources such as land, with a corresponding impact on price of processed food (Ringler et al., 2016).

Furthermore, the competitiveness of seafood commodities in foreign market would fall. In Scotland, the seafood production (mainly fishing and aquaculture) is export oriented, which makes the demand

for seafood commodities sensitive to foreign price changes (Graziano et al., 2018). Our results show falling seafood exports in both Scenario 1 and 2 as response to fall in foreign price (Table B2). Reduced export demand also makes the domestic seafood productions decrease.

The model results show minor effects on food security in terms of household affordability. Unlike electricity, which is a necessary good for households, seafood commodities are substitutable by other food sources so that the small increase in seafood prices in the model has a negligible impact on households. However, the model identifies the macroeconomic linkages whereby the lower supply of seafood leads to higher seafood prices through the price mechanism and eventually reduces household affordability. Therefore if, as expected, the scale of the OWF sector increases, the impacts would become significant through macroeconomic linkages, with the reduction in the supply and affordability of seafood resulting in lower food security (e.g. Pelletier et al., 2014; Smith et al., 2010). In these contexts, seafood security is potentially strongly related to further development of OWFs. Therefore, these impacts on the seafood sector should be carefully considered under the nexus framework when assessing further development of OWFs in response to net-zero policy targets.

### **4.3 Sensitivity analysis**

The sensitivity analysis maps the reaction of sectoral output values to variations in the elasticity of substitution ( $\sigma_a^{el}$ ) between the two electricity production sectors in the generation of the composite electricity commodity. This elasticity reflects the degree to which a low-carbon offshore wind generation technology is substitutable for other electricity generation, which relates to the evolution of technical change between OWFs and fossil fuels (Acemoglu et al., 2012). At present OWFs are imperfect substitutes for non-intermittent fossil fuels as an intermittent energy source due to technical limitations around storability and transmission to the national grid (Madrigal and Stoft, 2012; Timilsina et al., 2012) .

Increasing the substitution elasticity where the price of OWF output is falling has two effects. First, it increases the output of the OWF sector, as OWF electricity is substituted for other electricity output. Second, the impacts of OWFs on the electricity commodity price will increase as the importance of the

OWF sector in the electricity commodity composite rises. The absolute size of the negative impacts on seafood sectors would also be reduced in line with the falling price of electricity. To test this, the elasticity ( $\sigma_a^{el}$ ) is increased under Scenarios 1 and 2. Results for the default fixed share ( $\sigma_a^{el} = 0$ ) are compared to those where there is some flexibility, with the two sectors as complements ( $\sigma_a^{el} = 0.5$ ) and weak substitutes ( $\sigma_a^{el} = 1.5$ ). The simulations are also instructive in that they identify the ease with which the share of OWFs in total electricity generation could be increased. These results are shown in Table 7.

As the elasticity of substitution between electricity sectors increases, the changes in output of the OWF sector becomes more significant and the impact on the other electricity sector is reduced, reflecting the reduction in the price of OWF production as against the other electricity sector. This is particularly the case for Scenario 2 where allowing substitution between two sectors increases the share of OWF in total electricity generation to 12% as it becomes a more price competitive energy source.

Raising the elasticity limits the proportionate reduction in the output of the fishing and fish processing sectors, but the change is relatively small. For aquaculture the same pattern emerges but the effect of varying the elasticity is greater. This is especially the case in Scenario 2, where the sector contracts by 5.11% with the default value but slightly increases by 0.85% when the two electricity generating sectors are substitutes. It is expected that being a luxury good, aquaculture is sensitive to price change so that aquaculture could benefit from the lower electricity price in Scenario 2.

Production sectors	Default (Fixed coefficients)	Complementary ( $\sigma_a^{el} = 0.5$ )	Substitutable ( $\sigma_a^{el} = 1.5$ )
Scenario 1			
Fishing	-2.75	-2.04	-1.99
Fish processing	-1.41	-1.01	-1.01
Aquaculture	-5.49	-4.02	-3.78
Other electricity	5.34	4.37	4.08
OWF electricity	5.34	7.05	12.31
Share of OWF	10.00	10.24	10.72
Scenario 2			
Fishing	-3.36	-1.18	-0.86
Fish processing	-1.86	-0.63	-0.56
Aquaculture	-5.11	-0.39	0.85
Other electricity	5.81	2.85	1.70
OWF electricity	5.81	10.37	25.66
Share of OWF	10.00	10.67	12.09

**Table 7** The sensitivity of selected sectoral outputs to alternative values of the elasticity  $\sigma_a^{el}$  (% change in sectoral output of seafood production and electricity generation sectors)

#### 4.4 Limitations

A CGE modelling framework is a powerful assessment tool for energy-food nexus analysis, but the present study still suffers from a number of limitations. The simulation results have focused primarily on the production and consumption interaction between OWFs and seafood from the macroeconomic perspective. Note that the model identifies only the competition between energy and marine sectors for economy-wide factors of production, labour and capital. In the approach adopted here we do not specify any direct systematic link as the result of the competitive use of scarce marine resources, such as the replacement of fishing grounds with OWF areas (Berkenhagen et al., 2010). Although aquaculture and fish processing are not directly affected by spatial conflict with OWFs, they would have the knock-on effects from reduced fish supply and the whole seafood production would be impacted from the nexus perspective. Furthermore, the model does not take into account that there may be positive impacts of OWFs on fish stocks with potential benefits to fisheries. These result from the artificial reef effects and/or the *de facto* fishery exclusion zones created by OWFs (Bergström et al., 2014; Langhamer, 2012;

Westerberg et al., 2013). The assumptions underlying all these features should be addressed in future iterations of the SEMM model. Future work could focus on improving the model structure to allow competition and reallocation of marine areas, which could provide a stronger direct link between OWFs and fishing activities and knock-on effects on seafood production (Qu et al., in preparation). A further step could be the adoption of an integrated approach combining biological/ecological and CGE models to take the assessment to the ecosystem level.

## **5. Conclusion and Policy Implication**

### **5.1 Conclusion**

With fast development and rapidly falling costs, OWFs are likely to play an important role in increasing energy security and reaching the net-zero emission target of the UK Government. In particular, the recently announced record-low strike price of OWFs from AR3 will encourage further deployment of OWFs. However, expanding OWFs may bring conflicts with seafood supply because of indirect impacts through macroeconomic linkages and direct impacts through displacing fishing effort, which could be described in the energy-food nexus approach. Therefore, identifying, quantifying and managing the nexus between offshore wind energy and seafood supply will be of great importance in achieving the GHG target without jeopardising other economic and social goals.

This research fills a gap in existing socioeconomic assessments by principally focusing on the sectoral impact of the expansion of OWFs on seafood production and on the associated household income, consumption and welfare effects across different household groups. We develop a CGE model to compare the macroeconomic impacts of OWF electricity costs that are higher (AR2) or lower (AR3) than the wholesale electricity price and to assess the direct physical impacts of OWFs on fishing activities. In particular, this model is designed for applied energy-food nexus analysis in the marine context with separately-identified OWF and seafood sectors.

This analysis suggests that the overall economic impact of OWFs would be negative when the cost of OWFs is higher than the wholesale electricity price but positive when their cost is lower. From the energy-food nexus perspective, high-cost OWFs would not enhance energy security. Although the

production of OWFs could be stimulated by the CfD scheme, households would not benefit. Only low-cost OWFs would benefit energy security and improve welfare by both expanding production and making electricity cheaper for households. Food security is slightly decreased through the macroeconomic linkages as an expansion in the output of OWF sector creates negative impacts on seafood sectors by bidding away the production factors. The direct impacts through displacement of the fishing effort are confined to the three seafood sectors, with negligible impacts on the rest of the economy as the affected sectors are small. As for the distributional effects on household groups, lower income households are sensitive to electricity price changes as electricity is an essential commodity for households. This suggests that low-cost OWFs would help mitigate fuel poverty, especially for the lowest-income households.

## **5.2 Policy implications**

To meet the ambitious targets for future net-zero emissions, large-scale production of offshore renewables in Scotland can be expected. The approach taken in this study can easily be adapted to analyse the impact of other offshore renewable energy sectors including, for example, floating OWFs and particularly tidal and wave energy as planned in Scotland (Scottish Government, 2015). As these other offshore renewable energies still operate under high cost, our Scenario 1 results suggest that the economy would be negatively impacted through increased production of electricity using such technologies though they are low-carbon intensive. The CfD scheme serves to stimulate the production of marine renewables so that they contribute towards the decarbonisation of electricity but in a costly way which reduces households' welfare. Only when the cost has declined to a competitive, subsidy-free level could the offshore renewables bring positive impacts on the economy and provide cheaper electricity to benefit households. In particular, given that electricity price plays an important part in consumer budgets, especially those from lower income households, relevant renewable energy policies should carefully consider their distributional effects.

Therefore the subsidisation of high-cost renewables is still under debate. On the one hand, where the subsidy encourages effective development of renewables to become mature technologies offering significant benefits for electricity supply diversity and industry creation, then the subsidy could be

considered as an investment generating future returns from the export of technology and intellectual property (Andersson et al., 2017; Jeffrey et al., 2013). Furthermore, subsidy might provide an incentive for investments to improve the local content in OWFs supply chains, which would bring greater economic benefits (Gilmartin and Allan, 2015; Graziano et al., 2017). On the other hand, although renewable energies become cheaper due to subsidies and learning-by-doing, they are not perfect substitutes for conventional energy. Moreover, fossil fuel price would decrease as demand initially fell so that it would eventually become competitive in the energy market (Kalkuhl et al., 2013).

The results from the sensitivity analysis highlight the importance of substitution of OWFs and this also applies to other offshore renewables. The renewable energy share in overall electricity generation depends to a degree on the elasticity of substitution between the renewable and conventional electricity generation. When the renewable energy still has high production cost, a subsidy could help increase its share in total electricity generation but even with high substitution values will only make slow progress. In comparison, sensitivity analysis results where renewables have low production cost demonstrate that the greater replacement of other conventional electricity with renewable energy implies a more rapid move towards low-carbon generation. The strong substitution relationship might become more feasible as innovation widens the range of technological possibilities, such as improvements in storability (Acemoglu et al., 2012). If high substitution is achievable, from the macroeconomic perspective, renewable energy targets to support net-zero goals will become more easily attainable.

As long as OWFs are expanding, there will typically be negative impacts on the seafood sectors through the macroeconomic linkages, mainly driven by the general equilibrium competition for production factors. Although reductions in seafood production do not have profound effects across the economy as a whole, these effects may be locally or regionally significant, and fishing activities are still traditionally and culturally important for Scotland (Scottish Government, 2015). Possible mitigation policies include compensation for fishing businesses operating near planned OWFs areas or the creation of a common fund allowing fishermen to diversify (Alexander et al., 2013). The Oil and Gas UK Fishermen's Compensation Fund, which compensates for damages to fishing gear from oil and gas infrastructures, could set a precedent for similar funds for OWFs (BEIS, 2018b). Quantifying the negative economic

implications on the fishing sector will help to determine the scale of funding required through such mitigation schemes.

In summary, this CGE model is a useful tool to help improve quantitative understanding of the energy-food nexus between OWFs and seafood production through the macroeconomic linkages. The results obtained clearly support the view that it is important to account for the economic linkage of OWFs and seafood production. It could be a highly useful tool to support policy design to balance conflicting food security, energy security and net-zero emission goals in the context of the marine environment.

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## **Appendix A** 8-sector SAM in the SEMM

The basic 2013 Scottish SAM table is taken from Katris et al. (2019). It records the flows of incomes and expenditures through the Scottish economy. It is disaggregated to 30 production activities and five households quintiles measured by weekly income. To analysis the nexus linkage between OWFs and seafood production, three seafood sectors and two electricity sectors have been disaggregated from the original 30 aggregated sectors in the 2013 SAM. The fishing sector is disaggregated from the original ‘Agriculture, forestry and fishing’ sector; the fish processing and aquaculture is disaggregated from the ‘Food (and Tobacco)’ sector; and the OWF electricity sector is disaggregated from the ‘Electricity, transmission and distribution’ sector.

Information on the production technologies of the three seafood sectors comes from the Scottish input-output (IO) table where these three sectors are already identified as independent sectors (Scottish Government, 2020). After separating out the fishing sector the remaining elements of the ‘Agriculture, forestry and fishing’ sector in the 2013 SAM become the agriculture sector. After disaggregation of the fish processing and aquaculture, the rest ‘Food and (Tobacco)’ in the 2013 SAM is aggregated into the industry sector.

Unlike seafood, the OWF electricity sector is not specifically recorded in the Scottish IO accounts. As discussed in Section 2.2 of the text, the SEMM assumes that 10% of electricity is generated by OWFs so that the total cost of the OWF electricity sector is determined. Once the total output of OWFs is determined, the shares of each input across individual commodities (i.e., intermediate inputs) and value-added (i.e., labour and capital) are multiplied by the total cost listed in the 2010 UK IO table that has been disaggregated by electricity production sectors in Allan et al. (2019). The remainder in the electricity account consists of the other electricity sector. The remaining 27 activities in the original SAM are aggregated into the industry or service sector.

The approach to disaggregate the household final demand on three seafood sectors is based on the methodology by Emonts-Holley and Ross (2014) and Katris et al. (2017). In general, the share of home consumption in total consumption of each commodity is estimated based on the household surveys. Two surveys are available, the Household Final Consumption Expenditure (HHFCE) matrix (Scottish Government, 2009) and the Living Cost and Food Survey by ONS (ONS, 2014). The previous 2009

Scottish SAM table also provide reliable information on household consumption on three seafood sectors (Ross and Emonts-Holley, 2016). Using these data, commodity consumption is disaggregated across household groups. The two electricity activities are aggregated into one commodity to be consumed by households so that the disaggregation of electricity consumption into OWF and other electricity is not required.

All elasticities assumed in the SEMM are shown in Tables A4 and A5. The source of elasticities is previous studies and listed in the tables. The priority choice on elasticity is UK-based works (e.g., Defra). When the elasticity for UK is not available, the SEMM adopts assumption based on developed country data (e.g., FAO).

**Table A1 Aggregated 8-sector 2013 Social Accounting Matrix for Scotland in SEMM**

	sec_ag	sec_fi	sec_fp	sec_aq	sec_of	sec_el	sec_in	sec_se	com_ag	com_fi	com_fp	com_aq	com_el	com_in	com_se	lab	cap	hh1	hh2	hh3	hh4	hh5	cor	gov	invsav	row	total
sec_ag									2344.3																		2344.3
sec_fi										249.4																	249.4
sec_fp											812.9																812.9
sec_aq												504.1															504.1
sec_of													623.7														623.7
sec_el													5605.1														5605.1
sec_in														44925.5													44925.5
sec_se															126467.4												126467.4
com_ag	368.2	0.0	75.1	0.4	0.8	10.0	880.6	133.9										98.6	138.4	171.8	206.8	270.5		10.8	86.5	969.2	3421.6
com_fi	0.1	0.0	72.9	0.0	0.0	0.0	1.5	4.1										1.1	1.6	1.9	2.3	3.0		0.2	-7.6	225.3	306.4
com_fp	1.6	0.0	55.9	0.3	0.0	0.0	25.4	68.7										26.8	38.6	47.7	54.3	75.0		0.0	4.6	743.1	1142.3
com_aq	0.1	0.0	68.9	92.3	0.0	0.1	1.3	7.5										2.3	3.2	4.0	4.8	6.2		0.3	-6.6	454.5	638.8
com_el	20.7	7.9	11.5	21.5	261.5	2135.8	1056.0	834.1										262.4	353.3	386.1	367.4	427.0		0.0	63.5	1961.2	8169.9
com_in	229.4	61.8	87.1	65.7	186.7	460.4	10299.0	6140.9										519.5	748.6	925.6	1053.5	1454.0		547.3	10442.0	27806.3	61027.8
com_se	409.1	25.5	136.5	80.0	65.4	233.3	5957.5	26682.5										4509.0	6546.7	8682.0	11474.9	16773.9		31106.3	3736.4	34770.1	151189.0
lab	410.4	36.5	243.3	59.3	40.8	647.4	16435.1	51466.6																			69339.4
cap	1408.7	100.1	54.8	181.6	40.1	1827.9	9083.7	36404.5																			49101.4
hh1																1095.4	345.7						2012.3	4915.6		974.0	9343.0
hh2																4459.9	686.3						358.6	6521.8		1238.0	13264.6
hh3																10474.3	1086.7						3579.5	5628.8		1552.7	22322.0
hh4																20170.8	1771.8						5609.0	3560.8		1515.1	32627.5
hh5																33139.0	6306.6						10122.8	1878.8		2300.4	53747.6
cor																	32527.2	104.5	241.6	675.9	1886.2	4879.7	0.0	16742.5		-706.2	56351.4
gov	-504.1	17.6	6.9	3.0	28.3	290.1	1185.5	4724.7									6377.2	958.6	2605.6	4634.0	7772.6	16359.4	5981.2		2407.1	12644.9	65492.6
invsav																		157.8	114.6	562.7	1830.0	5495.8	28688.0	-5420.6		-8400.5	23027.9
row									1077.3	57.0	329.4	134.6	1941.1	16102.3	24721.6			2702.4	2472.4	6230.3	7974.7	8002.9	0.0	0.0	6302.0		78048.3
total	2344.3	249.4	812.9	504.1	623.7	5605.1	44925.5	126467.4	3421.6	306.4	1142.3	638.8	8169.9	61027.8	151189.0	69339.4	49101.4	9343.0	13264.6	22322.0	32627.5	53747.6	56351.4	65492.6	23027.9	78048.3	

**Table A2** Production sector decomposition of SEMM

8-sector SAM in SEMM	sector titles	2013 30-sector SAM table (Katris et al., 2019)	2013 98-sector Scottish IO (Scottish Government, 2020)	2010 26-sector UK IO table (Allan et al., 2019)
1	Agriculture	1		
2	Fishing	1	4	
3	Fish processing	5	10	
4	Aquaculture	5	5	
5	OWF electricity	16	46	S12
6	Other electricity			S10, S11, S13
7	Industry	2 - 15, 17 - 20		
8	Service	21 - 30		

**Table A3** Comparison of Type 1 multiplier from 8-sector SAM in SEEM, 98-sector Scottish IO and 26-sector UK IO

	8×8 Aggregated SAM in SEMM	2013 98-sector Scottish IO (Scottish Government, 2020)	2010 26-sector UK IO (Allan et al., 2019)
Agriculture	1.413		
Fishing	1.435	1.596	
Fish processing	1.640	1.542	
Aquaculture	1.595	1.741	
OWF electricity	2.090	1.671	2.298
Other electricity	1.588		
Industry	1.415		
Service	1.298		

**Table A4** Production function behaviour parameters (based on Allan et al., 2014; Lecca et al., 2014)

Production Sectors	Elasticity of Substitution			
	Elasticity of aggregate input ( $\sigma_a^a$ )	Factor substitution elasticity ( $\sigma_a^{va}$ )	Elasticity of export transformation ( $\sigma_c^t$ )	Armington substitution elasticity ( $\sigma_c^q$ )
Agriculture	0.3	0.3	2	2
Fishing				
Fish processing				
Aquaculture			0.5	
Offshore wind electricity				
Other electricity				
Industry			2	
Service				

**Table A5** Consumption function behaviour parameters

	HH1	HH2	HH3	HH4	HH5	Reference
Income elasticities ( $e_{c,h}$ )						
Agriculture	0.35	0.30	0.25	0.10	0.05	0.2 (De Agostini, 2014; Lechene, 2000)
Fishing	0.70	0.60	0.50	0.40	0.30	0.27 (De Agostini, 2014; Lechene, 2000)
Fish processing	0.70	0.60	0.50	0.40	0.30	0.54 – marine fish (FAO, 2017)
Aquaculture	1.20	1.17	1.15	1.12	0.90	0.36 (Jussila et al., 2012)
Electricity	0.80	0.70	0.50	0.30	0.20	Assumed
Industry	1.15	1.13	1.10	1.08	0.90	1.1-1.22 (FAO, 2017)
Service	1.15	1.15	1.10	1.05	0.90	0.2-0.9 (National Infrastructure Commission, 2017)
Frisch parameter ( $\varphi$ )						
Frisch	-7.27	-5.34	-3.07	-1.92	-1.20	Creedy and Dixon (1998) $\log(-\varphi) = a - a \log(y + \theta)$ $(a = 18.566, \alpha = 1.719, \text{and } \theta = 10575)$

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## Appendix B Model results

**Table B1** Percentage changes (%) in production activity inputs and their prices

Variable	Scenario 1	Scenario 2	Scenario 3
<i>Production factor (QVA)</i>			
Agriculture	-0.38	-0.73	-0.02
Fishing	-2.78	-3.41	-13.60
Fish processing	-1.38	-1.84	-4.19
Aquaculture	-5.51	-5.15	-1.49
Other electricity	5.22	5.50	0.06
OWF electricity	50.31	-8.28	0.06
Industry	0.32	-0.13	0.07
Services	-0.26	-0.07	0.02
<i>Production factor price (PVA)</i>			
Agriculture	0.17	0.22	-0.02
Fishing	0.15	0.21	0.99
Fish processing	-0.06	-0.03	0.01
Aquaculture	0.16	0.22	-0.02
Other electricity	0.16	0.21	-0.02
OWF electricity	0.06	0.11	-0.01
Industry	0.01	0.05	0.00
Services	0.03	0.07	0.00
<i>Intermediate input (QINT)</i>			
Agriculture	-0.34	-0.67	-0.03
Fishing	-2.72	-3.30	-13.34
Fish processing	-1.42	-1.87	-4.27
Aquaculture	-5.48	-5.07	-1.48
Other electricity	5.44	6.08	0.06
OWF electricity	50.51	-7.95	0.06
Industry	0.34	-0.08	0.07
Services	-0.25	-0.05	0.02
<i>Intermediate input price (PINT)</i>			
Agriculture	0.04	0.03	-0.01
Fishing	-0.06	-0.16	-0.01
Fish processing	0.09	0.07	0.26
Aquaculture	0.05	-0.07	-0.04
Other electricity	-0.54	-1.58	-0.01
OWF electricity	-0.36	-1.06	-0.01
Industry	-0.03	-0.10	-0.01
Services	0.00	-0.01	0.00

**Table B2** Percentage changes (%) in foreign exchange rate, exports, and imports

Variable	Scenario 1	Scenario 2	Scenario 3
EXR	-0.01	-0.04	0.01
<i>Exports (QE)</i>			
Agriculture	-0.63	-1.09	0.03
Fishing	-2.79	-3.41	-13.74
Fish processing	-1.43	-1.89	-4.31
Aquaculture	-5.55	-5.16	-1.47
Electricity	6.83	10.22	0.11
Industry	0.33	-0.15	0.10
Service	-0.32	-0.23	0.05
<i>Imports (QM)</i>			
Agriculture	0.27	0.20	-0.16
Fishing	-0.85	-1.14	-0.66
Fish processing	-0.17	0.04	-0.02
Aquaculture	-2.74	-2.69	-2.57
Electricity	2.51	-2.34	-0.05
Industry	0.34	0.07	-0.05
Service	-0.14	0.24	-0.03

**Table B3** Percentage changes (%) in household consumption and government consumption (real absorption)

Variable	Scenario 1	Scenario 2	Scenario 3
<i>Household consumption (<math>\sum_h QH_h</math>)</i>			
Agriculture	-0.09	-0.03	0.00
Fishing	-0.23	-0.05	-0.31
Fish processing	-0.20	-0.08	-0.06
Aquaculture	-0.62	-0.11	0.05
Electricity	-0.07	0.41	0.00
Industry	-0.44	-0.23	0.00
Service	-0.47	-0.20	-0.01
<i>Government consumption (QG)</i>			
Agriculture	-0.12	-0.15	0.01
Fishing	-0.22	-0.24	-1.64
Fish processing	-0.08	-0.10	-0.32
Aquaculture	-0.30	-0.24	0.11
Electricity	0.72	2.15	0.01
Industry	0.01	0.01	0.01
Service	-0.03	-0.06	0.00